Design, development and characterization of piezoresistive and capacitive polymeric pressure sensors for use in compression hosiery

Design, Development and Characterization of Piezoresistive and Capacitive Polymeric Pressure Sensors for use in Compression Hosiery

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Background

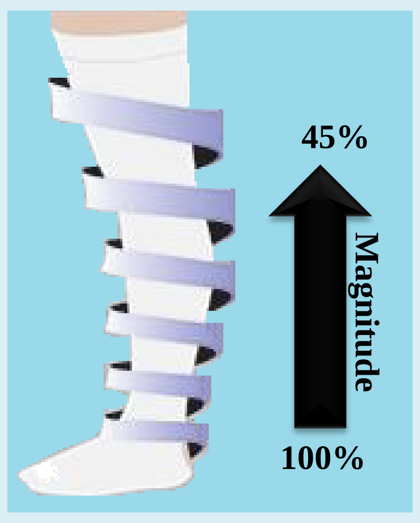

Fig.1: Compression hosiery

Medical pressure garments employ compression to treat a number of conditions such as varicose veins, chronic venous insufficiency, leg ulcers and hypertrophic scars. The amount of pressure they apply onto the body lies in the 0.5-6kPa regime, and there is a need of a cost-effective and reliable pressure sensor system to monitor their performance. This project was concerned with the development of pressure sensors utilizing flexible conductive and non-conductive polymers as the sensing elements and specifically for the application on compression hosiery.

Project Aims

- Develop piezoresistive pressure sensor based on conductive composites
- Develop capacitive pressure sensor based on tuneable polymeric medium
- Evaluate sensors' performance under compressive loads
- Investigate ways of embedding developed sensors onto compression hosiery

Piezoresistive pressure sensor

Polymeric conductive composites are multi-constituent systems, composed of a polymeric matrix and conductive filler particles, that exhibit a piezoresistive response when deformed. The developed piezoresistive pressure sensor utilizes a conductive polymer composite positioned in between a configuration of a structured and unstructured electrode (Fig.2). Two conductive composites were tested as the sensing element of the sensor: multi-walled carbon nanotubes-PDMS (MWCNT-PDMS) composite and Quantum Tunnelling Composite (QTC).

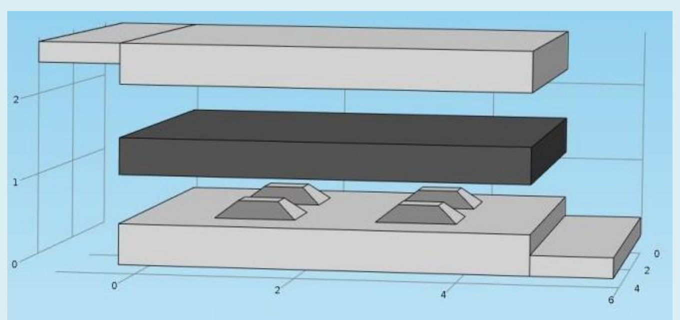

Fig. 2: Sensor Design

MWCNT-PDMS composites own their conductivity to the formation of a percolating network of filler particles (Fig. 3). The composite was developed via direct ultra-sonication and use of an organic solvent to assist dispersion. MWCNT-PDMS composites, with a filler concentration near the percolation threshold, exhibited a positive piezoresistive response when subjected to compression due to the large curvatures experienced by the CNTs. This response was substantially amplified when one of the electrode layers was structured (Fig. 4).

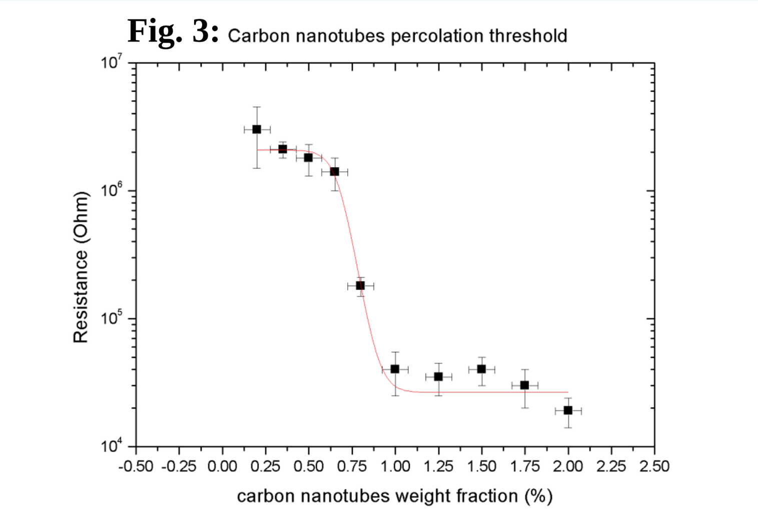

Fig. 3: Carbon nanotubes percolation threshold

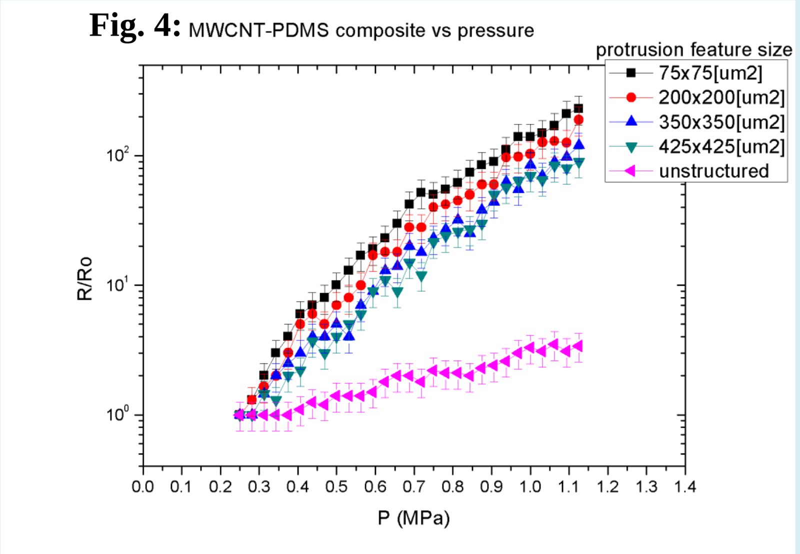

Fig. 4: MWCNT-PDMS composite vs pressure

QTC composites, developed and distributed exclusively by Peratech Inc, are composed of nano-spiked nickel particles completely coated in silicone-rubber. The developed QTC sensor was effectively insulating under no stress but exhibited an improved sensitivity under compressive loads (Fig. 5). As the composite was subjected to deformation its resistance dropped exponentially due to the quantum tunnelling between neighbouring nickel particle spikes. Similarly the sensor's performance was significantly improved when a structured electrode was utilized (Fig. 6).

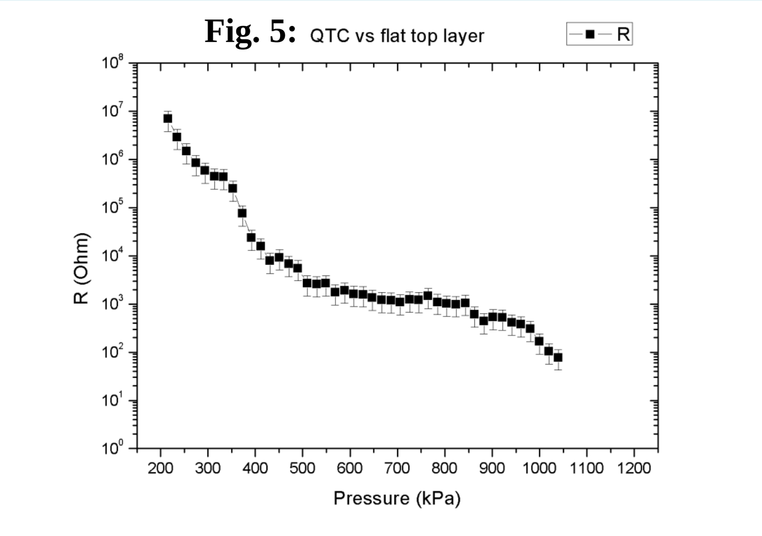

Fig. 5: QTC vs flat top layer

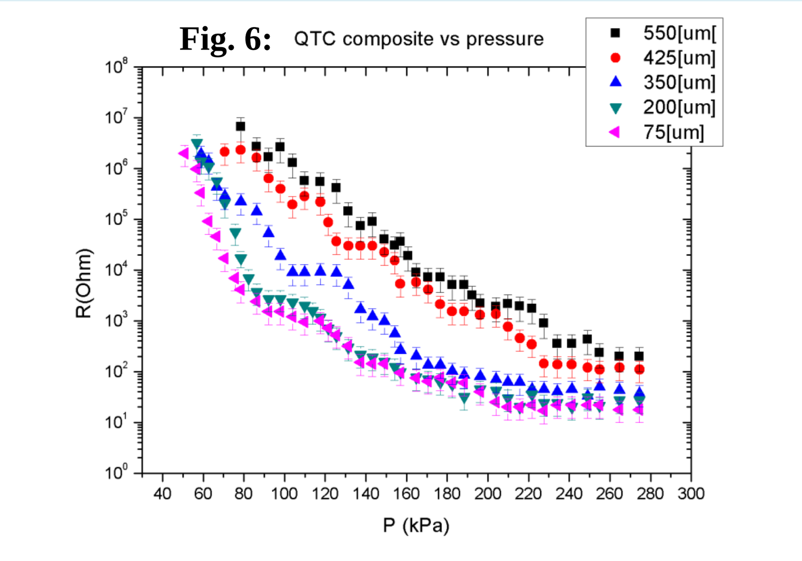

Fig. 6: QTC composite vs pressure

Capacitive pressure sensor

Flexible capacitive sensors are generally composed of two parallel electrodes, kept in close proximity via a deformable dielectric medium. The sensor's pressure sensitivity is dependant of the capacitor's capacitance change under stress, which in turn is a function of the system's initial capacitance, applied pressure and the Young's modulus of the dielectric medium:

$$\Delta C = C - C_0 = \varepsilon_o \varepsilon_r A \frac{\Delta d}{d \cdot (d - \Delta d)}$$

$d >> \Delta d$ $\qquad \sigma = \varepsilon \cdot E$

$$\Delta C \approx C_0 \cdot \frac{\sigma}{E}$$

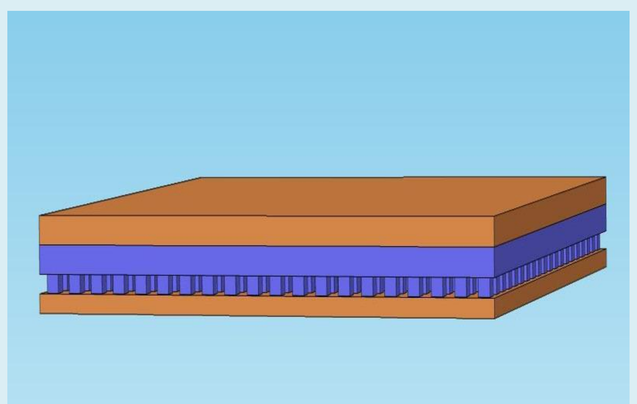

Fig. 7: Sensor Design

The developed capacitive pressure sensor is composed of a polymeric ultra-thin film (~30μm) embedded in between two copper-coated polyimide layers (Fig. 7). The polymer film thickness was controlled via spin coating (Fig. 8) and manipulation of the film's Young's modulus was achieved by employing a PDMS blend of Sylgard 184/Sylgard 527. The blend exhibits a tuneable Young's modulus depending on the ratio of the two constituents (Fig. 10). The polymer film was additionally structured with 18μm high square pillars to allow larger deformations (Fig. 9), which was achieved by utilizing a sacrificial photoresist mould during spin coating.

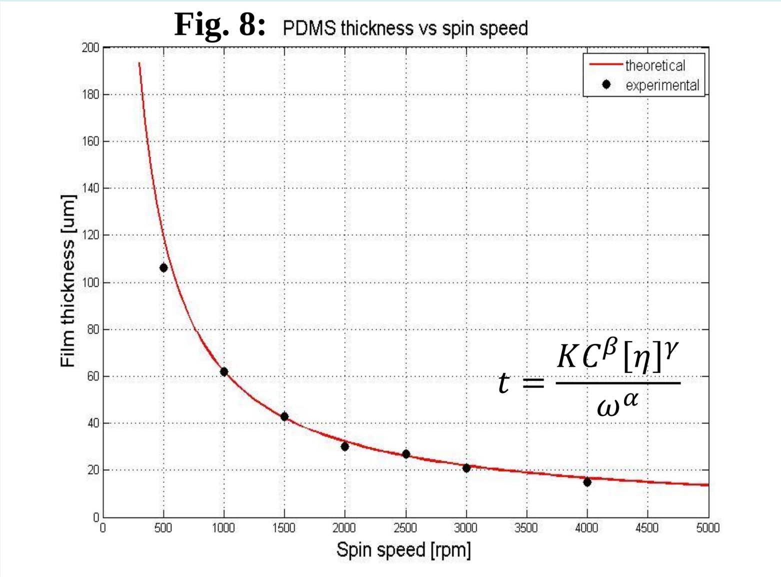

Fig. 8: PDMS thickness vs spin speed

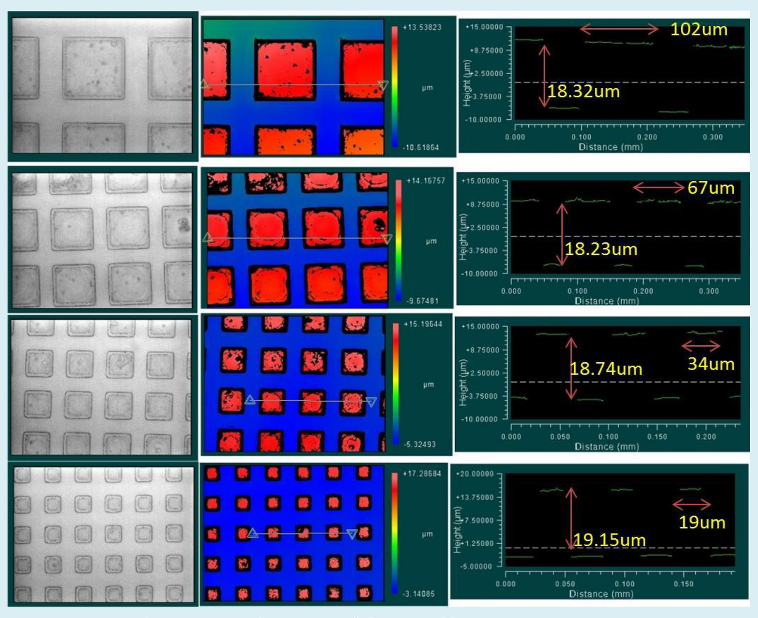

Fig. 9: Polymer film pillar structures

The combination of structuring the polymeric film, while maintaining an ultra-thin film thickness, and employing a PDMS blend with significantly lower Young's modulus (E=50-130kPa) than normal PDMS elastomers (E=1.7MPa) resulted in a capacitive pressure sensor sensitive within the working range (0-6kPa) of compression hosiery (Fig. 11).

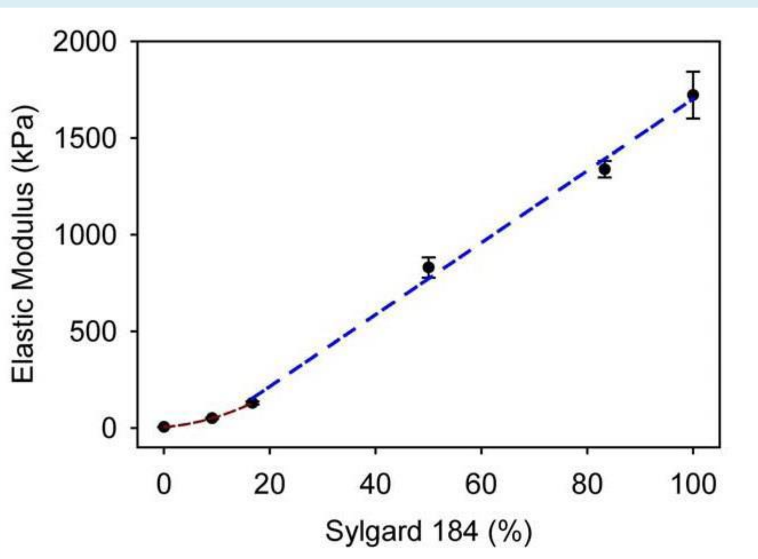

Fig. 10: PDMS blend Young modulus vs Sylgard 184 ratio [Rachele N. et al, 2012]

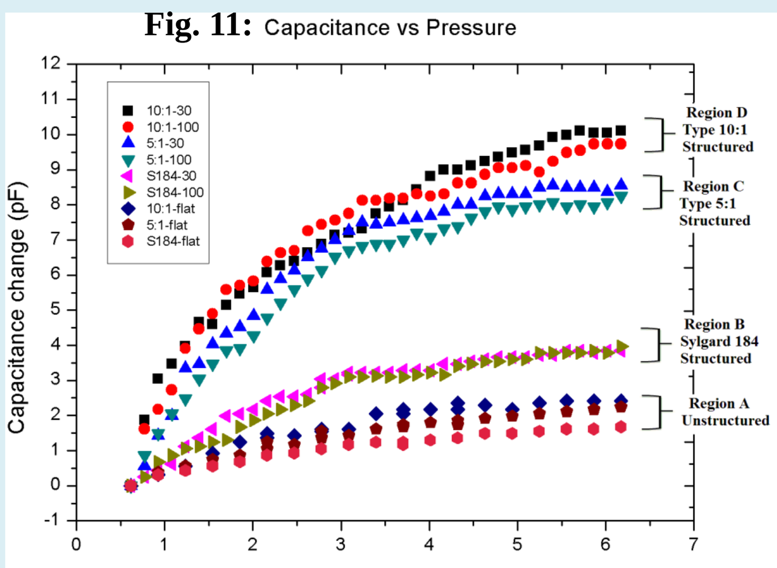

Fig. 11: Capacitance vs Pressure

Summary

- Developed a fabrication protocol for MWCNT-PDMS conductive composite and mapped percolation behaviour
- Developed MWCNT-PDMS/QTC sensors and evaluated their performance under compressive loads
- Developed a capacitive pressure sensor that utilizes an ultra-thin structured PDMS blend with tuneable mechanical properties
- Achieved pressure sensitivity within the working range of compression hosiery

Future work

- Develop all-elastomer capacitive sensor with conductive-composite layers
- Develop standalone garment-sensor pressure system
- Embed system onto compression hosiery and evaluate performance